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Report: The Carbon Cycle Revisited

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Introduction

In developing an integrated perspective on the earth system, it has been essential to use simplified conceptual models representing the pool sizes and flux rates between major earth system components. The carbon cycle, because of the integral role it plays in the earth system, has served as a focal point for developing these models. From carbon-based models, new models have been developed, studies have been initiated, and insights have been gained. To achieve greater understanding of the controls and dynamics of the earth system as represented by the conceptual model of the carbon cycle, it is beneficial to review our current state of knowledge regarding the carbon cycle to identify critical gaps in our understanding of the earth system.

Discussions during the Global Change Institute indicated a need to present, in some detail and as accurately as possible, our present knowledge about the carbon cycle, the uncertainties in this knowledge, and the reasons for these uncertainties. Figure 1 provides an overview of the carbon cycle. By its very nature, a diagram of this sort understates key assumptions and oversimplifies the interlinking processes, so it may be misleading without rather precise annotations. Figure 1 is based on extensive research over a number of years and is not merely a rough qualitative overview, but all aspects of this research are not apparent from the condensed information in the figure. The extensive comments below offer a fuller appreciation of our present knowledge. Following these comments, we discuss basic issues of internal consistency within the carbon cycle, and end by summarizing the key unknowns.
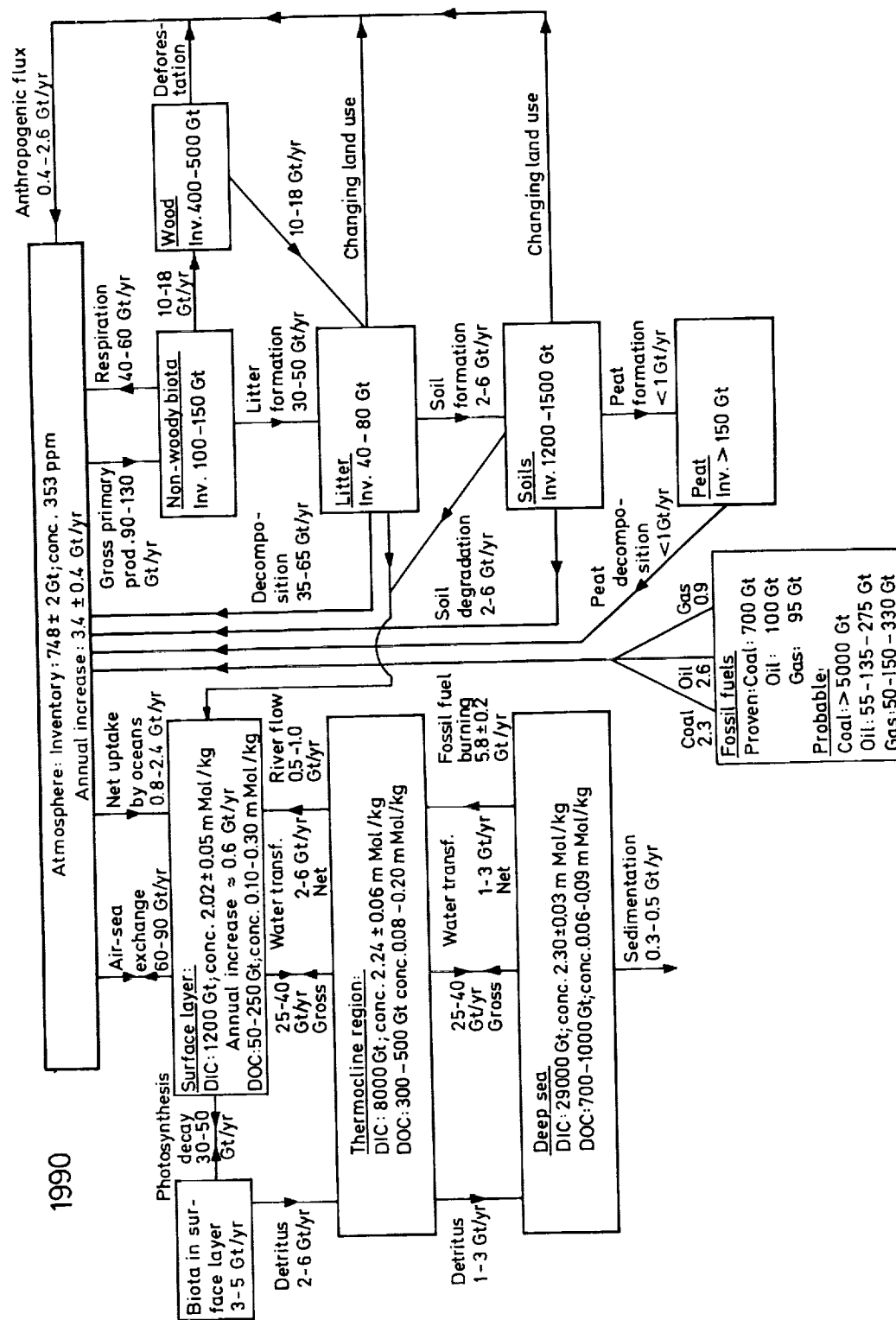
1990

Anthropogenic flux
0.4 – 2.6 Gt/yr

Atmosphere: Inventory: 748 ± 2 Gt; conc. 353 ppm
Annual increase: 3.4 ± 0.4 Gt/yr

Defores-
tation

Wood
Inv. 400–500 Gt

Changing land use

10–18 Gt/yr

Respiration
40–60 Gt/yr

10–18
Gt/yr

Non-woody biota
Inv. 100–150 Gt

Litter
formation
30–50 Gt/yr

Soil
formation
2–6 Gt/yr

Changing land use

Gross primary
prod. 90–130
Gt/yr

Litter
Inv. 40 – 80 Gt

Soils
Inv. 1200–1500 Gt

Peat
formation
<1 Gt/yr

Peat
Inv. > 150 Gt

Decompo-
sition
35–65 Gt/yr

Soil
degradation
2–6 Gt/yr

Peat
decompo-
sition
<1 Gt/yr

Gas
0.9

Coal   Oil
2.3   2.6

Fossil fuels
Proven: Coal: 700 Gt
        Oil: 100 Gt
        Gas: 95 Gt
Probable:
  Coal: >5000 Gt
  Oil: 55 – 135 – 275 Gt
  Gas: 50 – 150 – 330 Gt

Net uptake
by oceans
0.8–2.4 Gt/yr

Air-sea
exchange
60–90 Gt/yr

Surface layer:
DIC: 1200 Gt; conc. 2.02±0.05 m Mol/kg
Annual increase ≃ 0.6 Gt/yr
DOC: 50–250 Gt; conc. 0.10–0.30 mMol/kg

River flow
0.5 –1.0
Gt/yr

Water transf.
2–6 Gt/yr
Net

Fossil fuel
burning
5.8 ± 0.2
Gt/yr

Photosynthesis
decay
30–50
Gt/yr

Thermocline region:
DIC: 8000 Gt; conc. 2.24 ± 0.06 m Mol/kg
DOC: 300 –500 Gt conc. 0.08 – 0.20 mMol/kg

Water transf.
1–3 Gt/yr
Net

25–40
Gt/yr
Gross

Biota in sur-
face layer
3–5 Gt/yr

Detritus
2–6 Gt/yr

Deep sea
DIC: 29000 Gt; conc. 2.30±0.03 m Mol/kg
DOC: 700–1000 Gt; conc. 0.06–0.09 mMol/kg

Detritus
1–3 Gt/yr

25–40
Gt/yr
Gross

Sedimentation
0.3–0.5 Gt/yr

Figure 1. The carbon cycle. The magnitudes of the carbon compartments are given in gigatons (Gt: 10⁹ ton) C, which are equal to pentagrams (Pg: 10¹⁵ g). The fluxes between these are expressed in Gt C/yr = Pg C/yr.

Compartments

Atmosphere

Inventory: 748 ± 2 Gt C, based on the present (i.e., A.D. 1990) annual mean concentration of 353 ± 1 ppmv (1 ppmv CO_2 = 2.12 Gt C).

Annual increase: Rate of 3.4 ± 0.4 Gt C corresponds to 1.6 ± 0.2 ppmv/yr (cf. Watson et al., 1990; Tans et al., 1990).

Oceans

Total ocean volume: 1370 x 10^{15} m^3. The best estimate of the total amount of dissolved inorganic carbon (DIC) in the ocean is 38,000 ± 700 Gt C, based on this volume and an average DIC concentration of 2.27 ± 0.04 mMol/kg.

Surface layer: Usually defined as the top 100 m of warm surface water and about 200 m (sometimes more) of cold surface water. Volume: ca. 50 x 10^{15} m^3; the precise volume is somewhat arbitrary.

Surface layer DIC: 1200 Gt; average concentration assumed to be 2.02 ± 0.05 mMol/kg (Takahashi et al., 1981); the uncertainty is partly dependent on the thickness of the layer. An annual increase of ocean surface carbon concentrations of about 0.05%/yr is taking place due to transfer of CO_2 from the atmosphere to the sea (assuming that quasi-equilibrium between the atmosphere and the sea is approximately being maintained and that the average Revelle factor is 10; see Rintoul report, this volume). Model calculations suggest that since preindustrial time an increase of this reservoir by 2–2.5%, i.e., 24–30 Gt C, has occurred (cf. Maier-Reimer and Hasselmann, 1987; Bacastow and Maier-Reimer, 1990).

Surface layer dissolved organic carbon (DOC): 50–250 Gt C; uncertainty due to few data available. Those available, if globally representative, show concentrations of about 0.2 mMol/kg, corresponding to a total amount of 120 Gt C.

Surface layer biota: 3–5 Gt C, estimated indirectly by assuming that the amount present at any time is about 10% of the annual net primary production (NPP), i.e., the turnover time for biota in the surface layer is assumed to be about one month (de Vooys, 1979).

Thermocline: On the average extending to about 1000 m in tropical and midlatitude regions, absent in polar regions. Volume 300 x 10^{15} m^3.

Thermocline DIC: 8000 Gt C; average concentration assumed to be 2.24 ± 0.06 mMol/kg (Takahashi et al., 1981); uncertainty is partly dependent on the definition of the size of the reservoir. This reservoir is estimated to have increased by 75–125 Gt C since early last century due to transfer of excess carbon dioxide from the atmos-

phere directly or via the ocean surface layer (cf. Maier-Reimer and Hasselmann, 1987; Moore et al., 1989).

Thermocline DOC: 300–500 Gt C, primarily in the upper half of the region; uncertainty due to very few data. The concentration seems to decline from the surface values given above to about 0.08 mMol/kg in the lower part of the region.

Deep sea (including the outcrop regions in the polar seas): Volume 1020×10^{15} m^3.

Deep sea DIC: 29,000 Gt C; average concentration assumed to be 2.30 ± 0.03 mMol/kg (Takahashi et al., 1981); uncertainty is partly dependent on the definition of the size of the reservoir.

Deep sea DOC: 700–1000 Gt C; average concentration assumed to be 0.06–0.09 mMol/kg; less relative uncertainty than for the surface layers because of a more homogeneous distribution as revealed by ^{14}C values of about 0.65, implying a radiocarbon age of 3000–4000 years (cf. Williams, 1975).

Terrestrial System

Biota (nonwoody plus wood): 500–650 Gt C; assessment by direct inventory estimate. About 80% is judged to reside in wood (cf. Ajtay et al., 1979; Olson et al., 1983).

Litter: 40–80 Gt C (cf. Ajtay et al., 1979; Olson et al., 1983); dead roots may not have been adequately accounted for.

Soils: 1200–1500 Gt C (cf. Ajtay et al., 1979; Schlesinger, 1984); this estimate may to some extent include dead roots. It generally represents organic matter above about 50 cm depth.

Peat: >150 Gt C (cf. Ajtay et al., 1979); this is probably an underestimate, since peat often extends far below 50 cm, which usually is used for soil sample analysis.

Fossil fuels: Estimates of fossil fuel resources are given in Table 1.

Fluxes

Atmosphere–Ocean

This flux is 60–90 Gt C/yr. In steady state there is a mutual molecular exchange maintained by the partial pressure of carbon dioxide (pCO_2), preindustrially about 280 ppmv, in the atmosphere and the ocean. Given the 1973 pCO_2 of 328 ppmv, this yields an estimated average residence time for a CO_2 molecule in the atmosphere of 8–12 years and an estimated exchange rate of 15–21 mol CO_2/yr/m^2. These estimates (cf. Bolin et al., 1981) are based on (1) determination of rate of radon evasion from the sea (Peng et al., 1979), (2) balance between ^{14}C radiocarbon invasion into the sea

Table 1: Fossil fuel reserves

	Coal (10^9 ton)	Oil (10^9 m^3)	Gas (10^{12} m^3)
Used until 1988	150	100	40
Proven reserves (1985)	700	100	95
Probable reserves, low/mean/high*	>5000	55/135/275	55/150/330

*95/50/5% probability
Energy content: 1000 m^3 gas = 1.03 tons of oil equivalent; 1 ton coal = 0.65 tons of oil equivalent.
Carbon content: Coal and lignite, 69%; oil, 84%; gas, 540 g/m^3
Relative CO_2 emission per unit of energy: gas, 1.0; oil, 1.5; coal, 1.8
From Schilling and Wiegand, 1987; White, 1987; cf. also Goldemberg et al., 1988.

and radioactive decay in the sea, and (3) rate of invasion of ^{14}C produced by nuclear bomb testing (Stuiver, 1980).

During preindustrial times a net evasion of CO_2 from the oceans in tropical latitudes was approximately balanced by a net invasion into the oceans in polar and subpolar latitudes, which were associated with poleward transfer in the atmosphere and equatorward transfer in the oceans. The net circulation is estimated to have been 2–4 Gt C/yr (Pearman and Hyson, 1986; Keeling et al., 1989a, 1989b). The derivation of this transfer rate is based on an evaluation of the transport capability of the atmosphere between tropical latitudes and polar regions and an assessment of differences between the average atmospheric concentrations of CO_2 in these regions of 1–1.5 ppmv, as evaluated from data taken around 1960 (cf. Keeling et al., 1989a, 1989b). This pattern has been markedly disturbed due to anthropogenic CO_2 emissions, primarily in the Northern Hemisphere. Fossil fuel burning, deforestation, and changing land use have created a mean excess of 5–10 ppmv of CO_2 in the atmosphere relative to the oceans. As a result, a net flux of CO_2 into the oceans takes place at present, which is estimated to be 08–2.4 Gt C/yr (cf. Bolin, 1986; Siegenthaler and Oeschger, 1987; Tans et al., 1990; Watson et al., 1990).

Within the Oceans

The following estimates are based both on direct measurements and on assessments with the aid of carbon cycle models (cf. Oeschger et al., 1975; Siegenthaler, 1983; Bolin, 1986; Maier-Reimer and Hasselmann, 1987; Sarmiento et al., 1992).

DIC in surface water used for marine biota production: 30–50 Gt C/yr; estimated from a large number of measurements of NPP.

Marine biota transferred into dead organic matter, detritus, and DOC, and partly mineralized in the surface layers within a month to a year: 30–50 Gt C/yr. This flux is, however, less than the total NPP referred to above because a part is transferred into the thermocline region (see below).

Detritus settling into the thermocline region: 2–6 Gt C/yr. Mineralization of detritus and DOC in the thermocline region: 2–6 Gt C/yr as estimated from the oxygen deficit (AOU, apparent oxygen utilization) in the layer.

Transfer of detritus and DOC into the deep sea and mineralization into DIC: 1–3 Gt C/yr; estimated on the basis of radiocarbon age of DIC in the deep sea (see below).

DIC (gross) exchange between the surface layer, thermocline region, and deep sea due to ocean circulation and turbulence: 25–40 Gt C/yr, estimated with the aid of present knowledge of ocean circulation; of turbulent transfer, including penetrative convection in polar regions; and of the radiocarbon age of DIC in the deep sea. Due to a DIC gradient between the deep sea and the surface layer, this leads to:

Net upward transfer of DIC to the thermocline region: 1–3 Gt C/yr, and to the surface layer: 2–6 Gt C/yr. Because of increased DIC in the surface layer during the 20th century caused by the transfer of excess carbon from the atmosphere to the sea, this upward transfer has decreased by 1–2.5 Gt C/yr, primarily from the thermocline region to the surface layer, which enhances the uptake by the oceans of excess atmospheric CO_2 (cf. above). Mineralization of detritus and/or DOC in the deep sea: 1–3 Gt C/yr, balancing the net upward transfer due to water motions (see above).

The fluxes as given above constitute the biological pump, which maintains a higher pCO_2 (400–700 ppmv) in the thermocline region and the deep sea than would be expected otherwise.

Atmosphere–Terrestrial Exchange (Preindustrial Estimates)

The following are direct estimates of undisturbed preindustrial conditions as obtained from field data gathered in major biomes (cf. Ajtay et al., 1979; Olson et al., 1983; Bolin, 1986).

• Gross primary production: 90–130 Gt C/yr

• Respiration: 40–60 Gt C/yr, i.e., NPP: 40–70 Gt/yr, of which about 25% is stored in wood

- Formation of dead organic matter, litter: 40–70 Gt C/yr

- Litter decay within a few years: 35–65 Gt C/yr

- Litter to organic carbon in soil: 2–6 Gt C/yr

- Soil decomposition: 2–6 Gt C/yr

- Peat formation as well as peat decomposition: <1 Gt C/yr.

Erosion of the Continents and Flux to the Ocean (Preindustrial Estimates)

The following estimates of preindustrial river loads have been calculated (cf. Kempe, 1979):

- HCO_3-C: 0.4 Gt C/yr

- DOC: 0.1 Gt C/yr

- Particulate organic carbon (POC): 0.1 Gt C/yr

- Inorganic, suspended C: 0.2 Gt C/yr

- Total: 0.8 Gt C/yr.

It is likely that the flux of carbon to the sea has increased due to anthropogenic activities, this being particularly so for the flux of DOC and POC.

Other Fluxes

Carbon flux from the ocean to the sea floor: Sediments of carbonates: 0.1–0.2 Gt C/yr; organic carbon, open sea: about 0.05 Gt C/yr; shallow seas, partially anthropogenic: 0.3–0.5 Gt C/yr (cf Kempe, 1979).

Deforestation and changing land use: Release of CO_2 into the atmosphere: 0.4–2.6 Gt C/yr; accumulated release from about 1750 to 1980: 80–140 Gt C. These direct estimates have been made by using information from national forest services, calibrated against field measurements from present activities as well as satellite observations (Houghton et al., 1987; Detweiler and Hall, 1988).

Fossil fuel combustion: At present 5.6–6.0 Gt C/yr; accumulated emissions since the beginning of the industrial revolution (about 1840) until 1985: 190–210 Gt C. At present, the respective contributions from burning coal, oil, and gas are approximately 40%, 44%, and 16%.

Constraints on the System

Due to a number of constraints on the system, it is not permissible to combine any numbers given for reservoir sizes and fluxes within the uncertainty ranges that have been assigned. These constraints are listed below.

- It should be noted that variations of atmospheric CO_2, during the period from A.D. 1000 until anthropogenic influences became significant, have been less than 3–5 ppmv for any period of a decade or two. Therefore, the mean net exchange between the atmosphere, on the one hand, and the oceans and the terrestrial system, on the other, must have been less than 1 Gt C/yr and probably less than 0.5 Gt C/yr. This close balance is remarkable in the light of the sizes of the different reservoirs and the gross exchanges that take place between them.

- This balance has been disturbed by emissions of CO_2 from the burning of fossil fuels, deforestation, and changing land use. The average fossil fuel input during 1980–1987 was 5.1–5.5 Gt C/yr, while that from deforestation and changing land use was 0.4–2.6 Gt C/yr, i.e., the total anthropogenic emissions were 5.9–8.1 Gt C/yr. The atmospheric increase during this same period was 2.8–3.4 Gt C/yr, while the oceanic uptake is computed to have been 1.6–3.0 Gt C/yr, i.e., the total sinks are 4.4–6.4 Gt C/yr. Although there is a slight overlap between the estimated ranges for the total sources and the total sinks, it seems likely that there is an additional unknown sink, the "missing sink."

- In addition to showing an upward trend, the atmospheric CO_2 data from the globally distributed network of monitoring sites also show that CO_2 concentrations are higher in the Northern Hemisphere than in the south, reflecting the dominance of the Northern Hemisphere midlatitude fossil fuel sources. In 1980–87 the average concentration difference between 82°N (Alert) and the South Pole was 3.0 ppmv. Tans et al. (1990) attempted to simulated the north-south CO_2 gradient in a three-dimensional atmospheric tracer transport model. If we accept the geographic distribution of the fossil fuel sources and an approximate distribution of land sources, a major sink is required in the Northern Hemisphere rather than in the Southern Hemisphere to match the atmospheric observations.

- The difference in CO_2 concentrations between the hemispheres during the preindustrial era is unknown and is a source of uncertainty in the above inference about the hemispheric distribution

of the sinks. Keeling et al. (1989a, 1989b) have extrapolated the concentrations back in time and estimated that the CO_2 concentration at the South Pole may have been about 2 ppmv higher than in the Northern Hemisphere in the 1700s. Even when this estimate is included in the calculations, the requirement of a comparatively large contemporary northern sink remains.

• The data from the Northern Hemisphere further indicate that the magnitude of the sinks in the North Atlantic and the North Pacific was significantly less than what is required to balance the carbon budget and that a land sink for anthropogenic CO_2 must be assumed. The mechanism of this missing sink is unknown.

• A major uncertainty remains, however, in that the estimate of the uptake by the oceans critically depends on the determination of the global distribution of pCO_2 in ocean surface water. Observations, particularly from the southern seas, are still few.

• Carbon cycles should be tested against data on total carbon, as well as against the distributions of $\delta^{13}C$ and $\Delta^{14}C$. The transient changes of the latter due to anthropogenic activities also put some constraints on the behavior of the system as a whole. The decrease of $\Delta^{14}C$ from the middle of last century until 1954 (the Suess effect) is thus consistent with the estimated past emissions of fossil carbon (free of ^{14}C), although the associated decrease of the concentrations in the surface water of the oceans has not been verified by measurements.

• M. Heimann and R. Keeling have carried out simulations using a three-dimensional ocean model, similar to those reported by Tans et al. (1990), including a simulation of the ^{13}C distribution in the 1980s. They found that a large land sink in the Northern Hemisphere does not match the observed $\delta^{13}C$ gradient. They confirm, however, that uptake by the Northern Hemisphere oceans would require a partial pressure difference between the atmosphere and the ocean far in excess of what is observed. A small land sink, approximately proportional to the net primary production, is in any case required to match available observations.

• It is further important to consider the history of the CO_2 balance since the 1700s and, in particular, to assess the integrated changes during this period. Houghton (1989) estimated both the total magnitude and the distribution with time of a missing sink for the period 1860–1985. Although such a residual is necessarily quite uncertain, it appears that there was no missing sink before about 1940. It was largest in the 1970s and has decreased since

then. A careful analysis of such modeling results with gradually improved models might reveal the nature of this sink or the inadequacy of other features of present carbon cycle models.

Key Questions and Suggestions for Further Research

The global carbon cycle remains a puzzle. The enigma is caused by the difficulty of making direct measurements and the paucity of such measurements. Increasingly complex models can be developed in order to estimate the relative importance of difference processes and interactions and to assess the sensitivity of atmospheric CO_2 concentrations to assumed changes in these processes. Critical areas with remaining questions and important research needs are listed below.

- What is the current distribution of pCO_2 in the oceans? What are the seasonal variations of oceanic pCO_2? What is the magnitude of the errors introduced by inadequate seasonal sampling in current estimates of the annual mean pCO_2, especially in the North Pacific and North Atlantic? What is the role of the marginal seas?

- What are the rate-limiting processes that determine the magnitude of the ocean uptake of anthropogenic CO_2? How can we improve our modeling of these processes? How can we improve the model calculations on time scales important for anthropogenic CO_2? Currently, various tracers whose input histories differ from that of fossil fuel CO_2 are used to calibrate/validate transport characteristics of various time scales in ocean models. The magnitude of the CO_2 uptake by the oceans in these models is very sensitive to the calibration procedure (e.g., Joos and Siegenthaler, 1989).

- What was the preindustrial distribution of CO_2 in the atmosphere and in the oceans? Was the Southern Hemisphere concentration higher than in the north, as suggested by Keeling's extrapolation of the Mauna Loa and South Pole records? If so, what processes were responsible for the elevated pCO_2 (relative to the atmosphere) in the southern oceans? Simulation of preindustrial ^{14}C distribution (Levin et al., 1987) may help test hypotheses of air-sea CO_2 exchange.

- Seasonal transport in atmospheric models of the global carbon cycle should be tested by the simulation of inert tracers. The validation has only been done in the annual mean.

- Establishment of a calibration standard for ^{13}C measurements and expansion of the network for monitoring atmospheric [13]C

must receive high priority, so that latitudinal gradients and long-term trends can be interpreted with confidence. Likewise, carbon cycle models must include ^{13}C together with CO_2 to constrain the partitioning between land and ocean sources and sinks.

- The interannual variations of CO_2 in the atmosphere provide clues to the carbon cycle's responses to perturbations. What transient shifts in the CO_2 balance between photosynthesis and decomposition have resulted from increasing CO_2 concentration and fluctuations in surface air temperature and precipitation? Similarly, the upper ocean temperature is known to have fluctuated in the past 30 years. How might these fluctuations in thermodynamics and associated dynamics affect the oceanic carbon cycle and be manifested in the atmospheric CO_2 record?

- How have the numerous carbon pools in the terrestrial biosphere been altered by deforestation, afforestation, and changing agricultural practices? How can we narrow the uncertainties in our estimates of the CO_2 sources that result from land use modification?

- The size of the different carbon pools and the dominant controls and turnover rates of each pool need to be determined. How would climate change and anthropogenic perturbations change substrate properties (such as pH and soil fertility) and alter photosynthesis, allocation, decomposition, and other dynamical properties of terrestrial ecosystems? What controls the geographic variations in these processes? Can the uncertainties of C flux into various pools be reduced to determine whether a Northern Hemisphere terrestrial sink for C exists?

References

Ajtay, G.L, P. Ketner, and P. Duvigneaud. 1979. Terrestrial primary production and phytomass. In *The Global Carbon Cycle* (B. Bolin, E. Degens, S. Kempe, and P. Ketner, eds.), SCOPE 13, John Wiley and Sons, Chichester, England.

Bacastow, R.B., and E. Maier-Reimer. 1990. Ocean-circulation model of the carbon cycle. *Climate Dynamics 4*, 95–126.

Bolin, B. 1986. How much CO_2 will remain in the atmosphere? The carbon cycle and projections for the future. In *The Greenhouse Effect, Climate Change and Ecosystems* (B. Bolön, B. Döös, J. Jäger, and R.A. Warrick, eds.), SCOPE 29, John Wiley and Sons, Chichester, England.

Bolin, B., C.D. Keeling, R.B. Bacastow, A. Björkström, and U. Siegenthaler. 1981. Carbon cycle modelling. In *Carbon Cycle Modeling* (B. Bolin, ed.), SCOPE 16, John Wiley and Sons, Chichester, England.

Broecker, W.S., T.-H. Peng, and R. Engh. 1980. Modeling the carbon system. *Radiocarbon 22*, 565–598.

Codispoti, L.A., G.E. Friederick, R.L. Iverson, and D.W. Hood. 1982. Temporal changes in the inorganic carbon system of the southeastern Bering Sea during spring 1980. *Nature 296*, 242–244.

Detweiler, R.P., and C.A.S. Hall. 1988. Tropical forest and the global carbon cycle. *Science 239*, 42–47.

de Vooys, C.G.N. 1979. Primary production in aquatic environments. In *The Global Carbon Cycle* (B. Bolin, E. Degens, S. Kempe, and P. Ketner, eds.), SCOPE 13, John Wiley and Sons, Chichester, England, 259–282.

Enting, I.G., and J.V. Mansbridge. 1989. Seasonal sources and sinks of atmospheric CO_2: Direct inversion of filtered data. *Tellus 41B*, 111–126.

Goldemberg, J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams. 1988. *Energy for a Sustainable World*. Wiley Eastern, New Delhi, India.

Houghton, R.A. 1989. The long-term flux of carbon to the atmosphere from changes in land use. In *Proceedings of the Third International Conference on Analysis and Evaluation of CO_2 Data, Present and Past*. Hinterzarten, 16–20 October 1989. Publication No. 59, WMO Environmental Pollution Research Programme, Geneva, Switzerland.

Houghton, R.A., R.D. Bone, J.R. Fruci, J.E. Hobby, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, G.M. Woodwell, B. Moore, D.L. Skole, and N. Myers. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of the global flux. *Tellus 29B*, 122–139.

Joos, F., and U. Siegenthaler. 1989. Study of the oceanic uptake of anthropogenic CO_2 and C-14 using a High-latitude Exchange/Iterior Diffusion-Advection (HILDA) model. In *Proceedings of the Third International Conference on Analysis and Evaluation of CO_2 Data, Present and Past*. Hinterzarten, 16–20 October 1989. Publication No. 59, WMO Environmental Pollution Research Programme, Geneva, Switzerland.

Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T.P. Whorf, M. Heimann, W.G. Mook, and H. Roeloffzen. 1989a. A three dimensional model of atmospheric CO_2 transport based on observed winds: 1. Analysis of observational data. In *Aspects of Climate Variability in the Pacific and the Western Americas* (D.H. Peterson, ed.), Geophysical Monograph 55, American Geophysical Union, Washington, D.C., 165–236.

Keeling, C.D., S.C. Piper, and M. Heimann. 1989b. A three dimensional model of atmospheric CO_2 transport based on observed winds: 4. Mean annual gradients and interannual variations. In *Aspects of Climate Variability in the Pacific and the Western Americas* (D.H. Peterson, ed.), Geophysical Monograph 55, American Geophysical Union, Washington, D.C., 305–363.

Kempe, S. 1979. Carbon in the rock cycle. In *Carbon Cycle Modeling* (B. Bolin, ed.), SCOPE 16, John Wiley and Sons, Chichester, England, 343–377.

Levin, I., B. Kromer, D. Wagenbach, and K.O. Münnich. 1987. Carbon isotope measurements of atmospheric CO at a coastal station in Antarctica. *Tellus 39B*, 89–95.

Maier-Reimer, E., and K. Hasselmann. 1987. Transport and storage of carbon dioxide in the ocean, and in organic ocean-circulation carbon cycle model. *Climate Dynamics 2*, 63–90.

Moore, B., B. Bolin, A. Björkström, K. Holmén, and C. Ringo. 1989. Ocean carbon models and inverse methods. In *Ocean Circulation Models: Combining Data and Dynamics* (D.L.T. Anderson and J. Willebrand, eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands, 409–449.

Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann. 1975. A box diffusion model to study the carbon dioxide exchange in nature. *Tellus 27*, 168–192.

Olson, J.S., J.A. Watts, and L.J. Allison. 1983. *Carbon in Live Vegetation of Major World Ecosystems*. Publication TR004, U.S. Department of Energy, Washington, D.C.

Pearman, G.I., and P. Hyson. 1986. Global transfer and inter-reservoir exchange of carbon dioxide with particular reference to stable isotopic distributions. *Journal of Atmospheric Chemistry 4*, 81–124.

Peng, T.-H., W.S. Broecker, G. Mathieu, and Y.-H. Li. 1979. Radon evasion rates in the Atlantic and Pacific Oceans as determined during the GEOSECS Program. *Journal of Geophysical Research 84*, 2471–2486.

Sarmiento, J.L., J.C. Orr, and U. Siegenthaler. 1992. A perturbation simulation of CO_2 uptake in an ocean circulation model. *Journal of Geophysical Research 97(3)*, 3621–3647.

Schilling, H.-D., and D. Wiegand. 1987. Coal resources. In *Resources and World Development* (D.J. McLaren, and B.J. Skinner, eds.), Dahlem Workshop, John Wiley and Sons, Chichester, England, 129–156.

Schlesinger, W.H. 1984. Soil organic matter: A source of atmospheric carbon dioxide. In *The Role of Terrestrial Vegetation in the Global Carbon Cycle* (G.M. Woodwell, ed.), SCOPE 23, John Wiley and Sons, Chichester, England, 111–127.

Schlosser, P., G. Bonisch, M. Rhein, and R. Bayer. 1991. Reduction of deep water formation in the Greenland Sea during the 1980s: Evidence from tracer data. *Science 251*, 1054–1056.

Siegenthaler, U. 1983. Uptake of excess CO_2 by an outcrop-diffussion model of the ocean. *Journal of Geophysical Research 88(C6)*, 3599–3608.

Siegenthaler, U., and H. Oeschger. 1987. Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice core data. *Tellus 39B*, 140–154.

Stuiver, M. 1980. ^{14}C distribution in the Atlantic Ocean. *Journal of Geophysical Research 85*, 2711–2718.

Takahashi, T., W.S. Broecker, and A.E. Bainbridge. 1981. The alkalinity and total carbon dioxide concentration in the world oceans. In *Carbon Cycle Modelling* (B. Bolin, ed.), SCOPE 16, John Wiley and Sons, Chichester, England.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. *Science 247*, 1421–1438.

Toggweiler, J.R. 1989. Is the downward dissolved organic matter (DOM) flux important in carbon transport? In *Productivity of the Ocean: Present and Past* (W.H. Berger, V.S. Smetacek, and G. Wefer, eds.), John Wiley and Sons, New York, 65–83.

Watson, R.T., H. Rodhe, H. Oeschger, and U. Siegenthaler. 1990. Greenhouse gases and aerosols. In *Climate Change: The IPCC Scientific Assessment*. Intergovernmental Panel on Climate Change and Cambridge University Press, Cambridge, England, 1–40.

White, D.A. 1987. Conventional oil and gas resources. In *Resources and World Development* (D.J. McLaren, and B.J. Skinner, eds.), Dahlem Workshop, John Wiley and Sons, Chichester, England, 113–128.

Williams, P.J.LeB. 1975. Biological and chemical aspects of dissolved organic matter in sea water. In *Chemical Oceanography* (J.P. Riley and G. Skirrow, eds.), Academic Press, London, 301–363.